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Testing of the OBO Bettermann Peak Current Sensor System for Lawrence Livermore National Laboratory

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Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Preface

Martin Uman was subcontracted during the 2004 lightning season to study possible explanations for anomalous high-current lightning measurements observed by the British. His work focused on the reliability of the OBO Bettermann peak current measurement system, which was used by the British in their measurement campaign. Two reports briefly summarizing the anomalous British measurements and detailing some of their work on the subject are David J. Newton's "Lightning Protection System Evaluation for Warhead and Explosive Processing Facilities (AWE Report 53/02)," February 2002 and "Peak Current Sensor Card Measurement Trials using Lightning Simulator at AEA Culham (AWE Report 653/04)," October 2004, by the same author.

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EXECUTIVE SUMMARY

During summer 2004 we studied the reliability of the OBO Bettermann peak current sensor (PCS) monitoring system – (1) credit card-type cards with magnetic strips and (2) a card reader. Three methods were used to generate current for testing the PCS system: 1) a Keytek current generator 2) a capacitor discharge, and 3) rocket triggered lightning. The data obtained from the cards were compared with oscilloscope measurements of the generated currents. Additionally, we tested for nearby natural and nearby rocket triggered lightning by placing cards on an airport runway lighting system lightning-protection counterpoise, on power line grounds, and on the lightning-protection system of an explosive storage igloo at Camp Blanding Army National Guard Base. In all experiments exposed cards were read multiple times to test the consistency of the measurement. Each card read zero before each experiment.

The Keytek current generator produced a maximum peak current of 5 kA which was unrecorded by the PCS system despite the OBO Bettermann claim that currents larger than 3 kA could be recorded. Three cards were exposed to triggered lightning current and gave proper results (the PCS card measurement deviated less than +- 2 kA from the peak current value measured by research equipment). Cards exposed to the current of the capacitor discharge, which was initiated by triggering a spark gap, generally yielded current readings about four times higher than the actual value, but proper readings were observed with some card orientations and locations. Two of the 7

cards tested with the Keytek and 4 of the 17 cards placed on the explosive storage igloo and on the runway counterpoise yielded non-zero current on some readings and zero current on other readings, while all other cards in those locations produced zero current for all readings of the card.

The cause of the apparently erroneously high current readings on the cards used in the capacitor discharge experiments is not understood, but the high values may well be related to (1) the direct electromagnetic radiation from the spark gap or from other parts of the current-carrying wire effecting the card's magnetic stripe in an unexpected way, and/or (2) the magnetic field from a potential short duration (nanosecond scale) breakdown current (not observable with our present instrumentation if indeed it does exists) in the current-carrying wire rather than from the oscillatory capacitor discharge current observed on the digitizing oscilloscope.

CHAPTER 1
INTRODUCTION

Measurements of peak current in the lightning protection systems of explosives storage structures in the UK made using the OBO Bettermann measurement system have yielded remarkably high peak current values, of the order of 100 kA. The currents are reportedly not associated with direct flash attachment to the structures but potentially could be associated with nearby lightning. The OBO Bettermann measurement system incorporates a plastic card with a magnetic stripe, with the appearance of a credit card. Our present study involves understanding under what conditions the cards and card readers yield accurate results and under what conditions they yield erroneous results. Controlled experiments, with test currents accurately measured by research measuring systems employing current transformers or non-inductive resistors (shunts) in conjunction with recording oscilloscopes, are used in an attempt to understand the degree of accuracy and consistency of the card and card reader.

CHAPTER 2
BACKGROUND INFORMATION

Description of the Peak Current Sensor System

The peak current sensor (PCS) system consists of credit-card type cards with a pre-magnetized magnetic stripe (Figure 2-1), a card holder (Figure 2-2), and a magnetic card reader (Figure 2-3). The cards are made of polycarbonate and have dimensions of 85.7 mm x 54 mm. The card holder is made of polypropylene and an elastomer seal and has dimensions of 115 mm x 72 mm x 7 mm (17 mm for the clamp). The card holder can clamp on an 8-10 mm diameter round wire. The magnetic card reader can operate on battery power (charging time 8 h) and has dimensions of 250 mm x 200 mm x 380 mm.

Figure 2-1: Peak current sensor card, front view and back view.

Figure 2-2: Peak current sensor card and card holder, front view and back view.

Figure 2-3: Peak current sensor card reader.

Functionality of the Peak Current Sensor System

The card is held in a card holder which is attached to a wire. The magnetic stripe has an impressed magnetic field pattern which is partially erased by the magnetic field of the current flowing through the wire. The magnetic card reader senses the magnetic field pattern of the card by swiping the read head from left to right and then from right to left so that the reading shows two symmetric field patterns[1], as illustrated in Figure 2-4.

The evaluation algorithm of the PCS card reader is described in the original pattern as follows. Note that the evaluation algorithm in the present system may be different. The card reader compares the magnetic field pattern read from the card with characteristics of reference magnetic field patterns that are associated with a specific peak current. The card reader determines the values of two levels of the magnetic field pattern (level 1 and level 2 indicated in Figure 2-4). The card reader selects a reference magnetic field pattern with the same level 1 value as the measured level 1 value. The level 2 value of selected reference pattern is obtained from the reader memory and compared with the measured level 2 value. If the measured level 2 value is within the tolerance window (indicated in Figure 2-4), then the card reader concludes that the reference pattern and the measured pattern were shaped by a surge current with the same peak (within the measurement tolerance) and the reader displays the peak current associated with the reference pattern.

For example, the magnetic field pattern in Figure 2-4 a) is recognized as an unexposed pattern, since the values for levels 1 and 2 are both at the same outer left position. In Figure 2-4 b) the card reader reads the value of level 1 and selects the 20 kA

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[1] The magnetic field pattern from left to center is recorded during the left to right movement of the read head and the magnetic field pattern from center to right is recorded during the right to left movement of the read head.

reference pattern, which has the same level 1 value. The measured level 2 is within the tolerance window and the measured magnetic field pattern is therefore determined to be similar to the reference pattern. The card reader displays 20 kA. The magnetic field pattern in Figure 2-4 c) due to a 40 kA current is analyzed in a similar fashion. The value of level 2 in Figure 2-4 d) does not fall within the tolerance window and the magnetic field pattern is therefore recognized as the pattern of a manipulated card (e.g., a card exposed to a permanent magnet).

According to manufacturer's specification, the peak current measurement system can measure current peaks between 3 and 120 kA with an accuracy of ± 2 kA. According to the manufacturer, the card is designed to maintain a record of only the largest current (magnetic field) to which it is exposed.

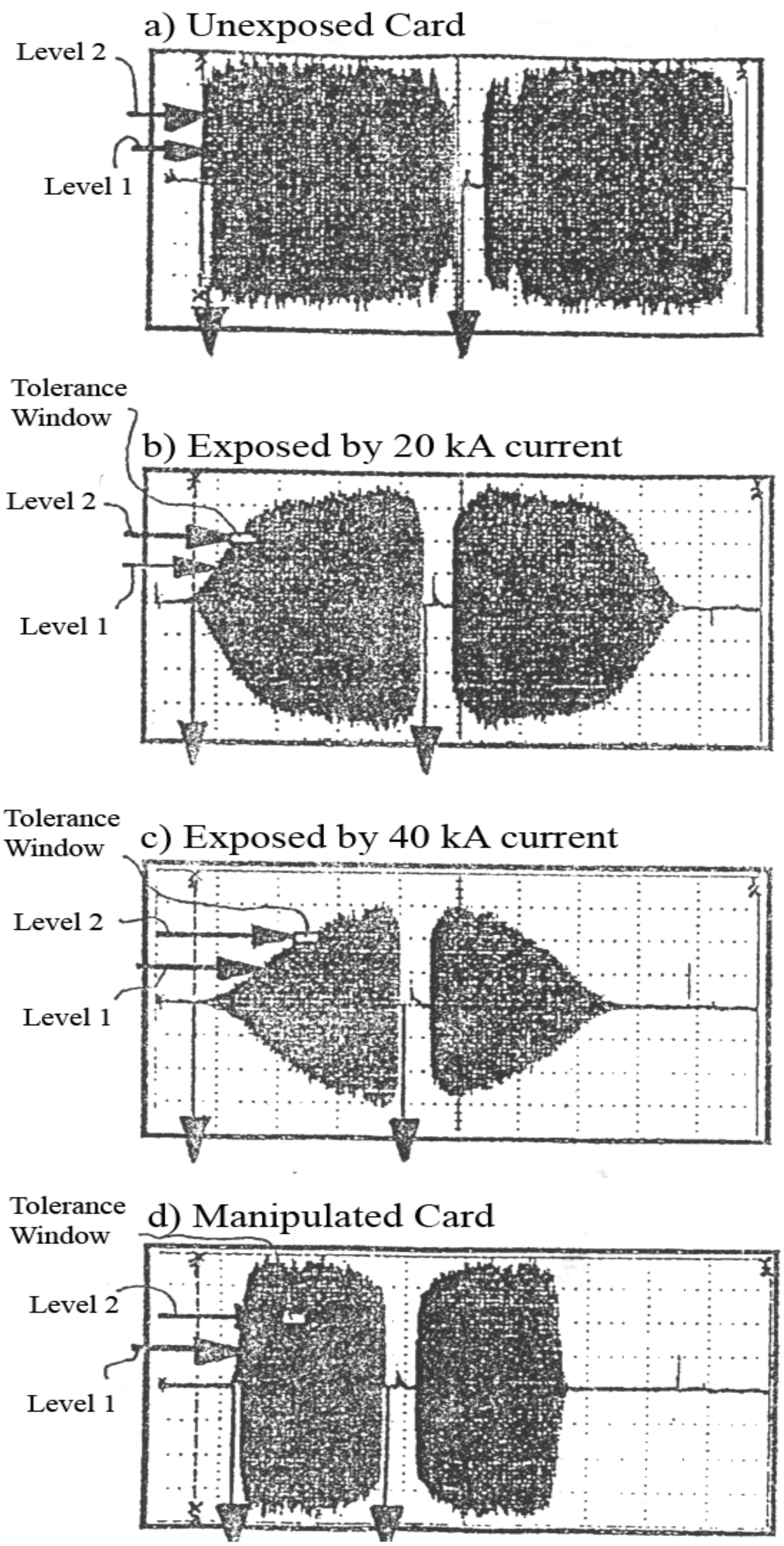

Figure 2-4: Magnetic field pattern of a) an unexposed card, b) a card exposed by a 20 kA current, c) a card exposed by a 40 kA current, and b) a manipulated card. Figure adopted from original patent which may not be how the present system is implemented.

Rocket Triggered Lightning

In rocket triggered lightning, a small rocket with an attached conducting wire is used to artificially initiate lightning (Figure 2-5).

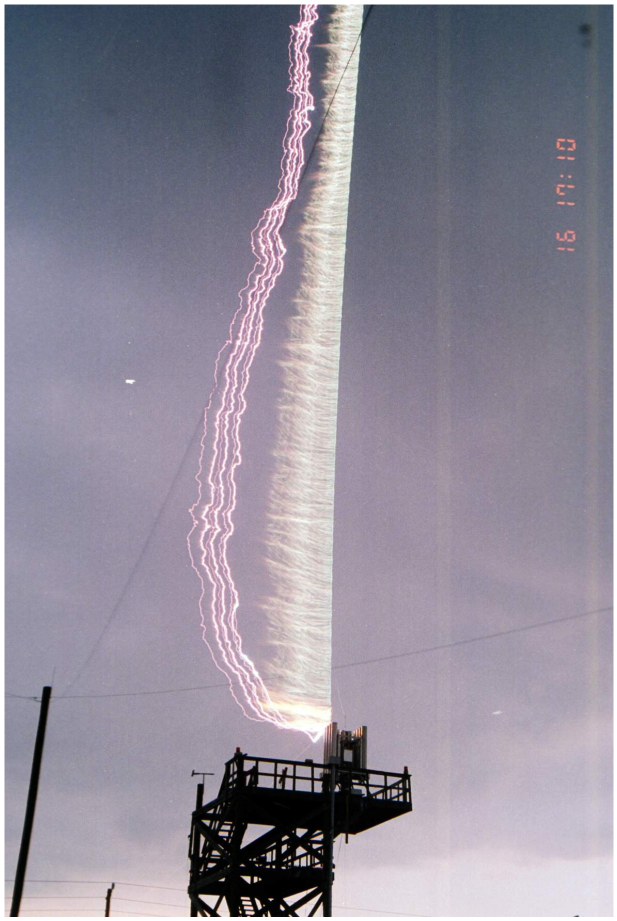

Figure 2-5: Rocket triggered lightning in Camp Blanding, Florida (Flash U9910).

Under favorable conditions, i.e., measured static electric field on ground < -5 kV/m, a rocket trailing a conducting wire is launched with a speed of about 200 m/s towards a thundercloud. In the classical rocket triggered lightning technique, illustrated in Figure 2-6 (adapted from Rakov, 1999), the triggering wire is a continuous conductor that is connected to ground. As the rocket ascends, the electric field at the tip of the rocket is distorted. When the rocket reaches an altitude of about 200 m to 300 m, the field enhancement at the rocket tip can result into the development of a positive leader (provided that a sufficient ambient negative field is present) ascending with a speed of the order of 10^5 m/s from the rocket tip towards the thundercloud. The upward-going positive leader vaporizes the wire and establishes an initial continuous current (ICC), which flows for typically some hundreds of milliseconds through the channel. After the cessation of the ICC, a no-current interval having a typical duration of tens of milliseconds occurs, which may be followed by one or more downward leader / upward return stroke sequences. These leader / return stroke sequences are believed to be very similar to the subsequent leader / return stroke sequences in natural lightning.

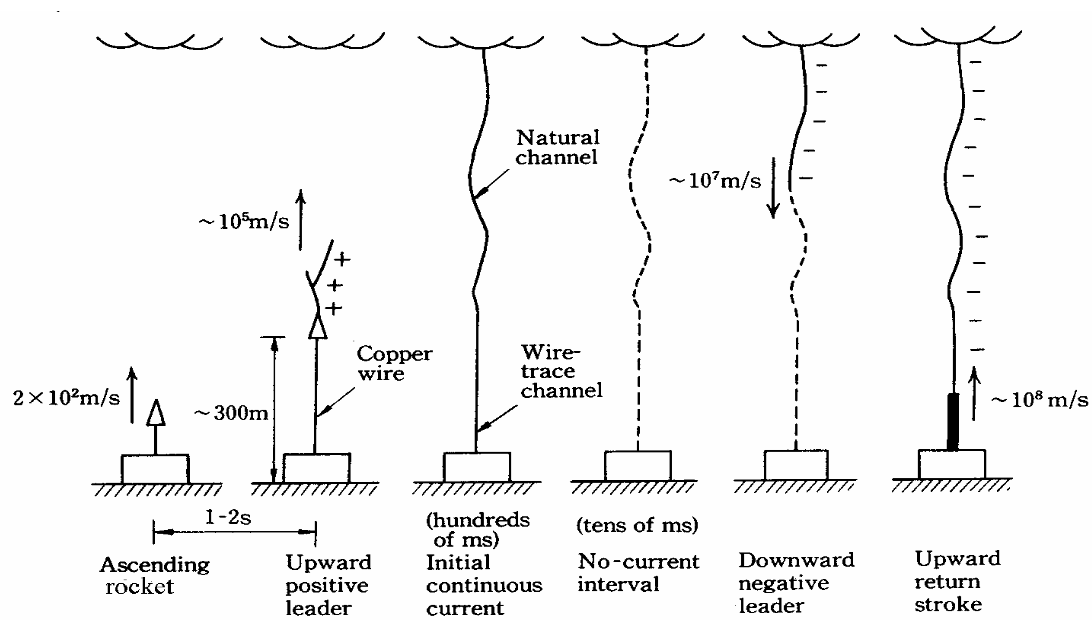

Figure 2-6: Sequence of events in classical rocket triggered.

International Center for Lightning Research and Testing at Camp Blanding

The International Center for Lightning Research and Testing (ICLRT) is an outdoor facility occupying about 100 acres (1 km^2) at the Camp Blanding, Florida Army National Guard Base, located approximately midway between Gainesville and Jacksonville, Florida and is used for triggering (artificially initiating) lightning from natural overhead thunderclouds using the rocket-and-wire technique. An overview of the ICLRT is shown in Figure 2-7.

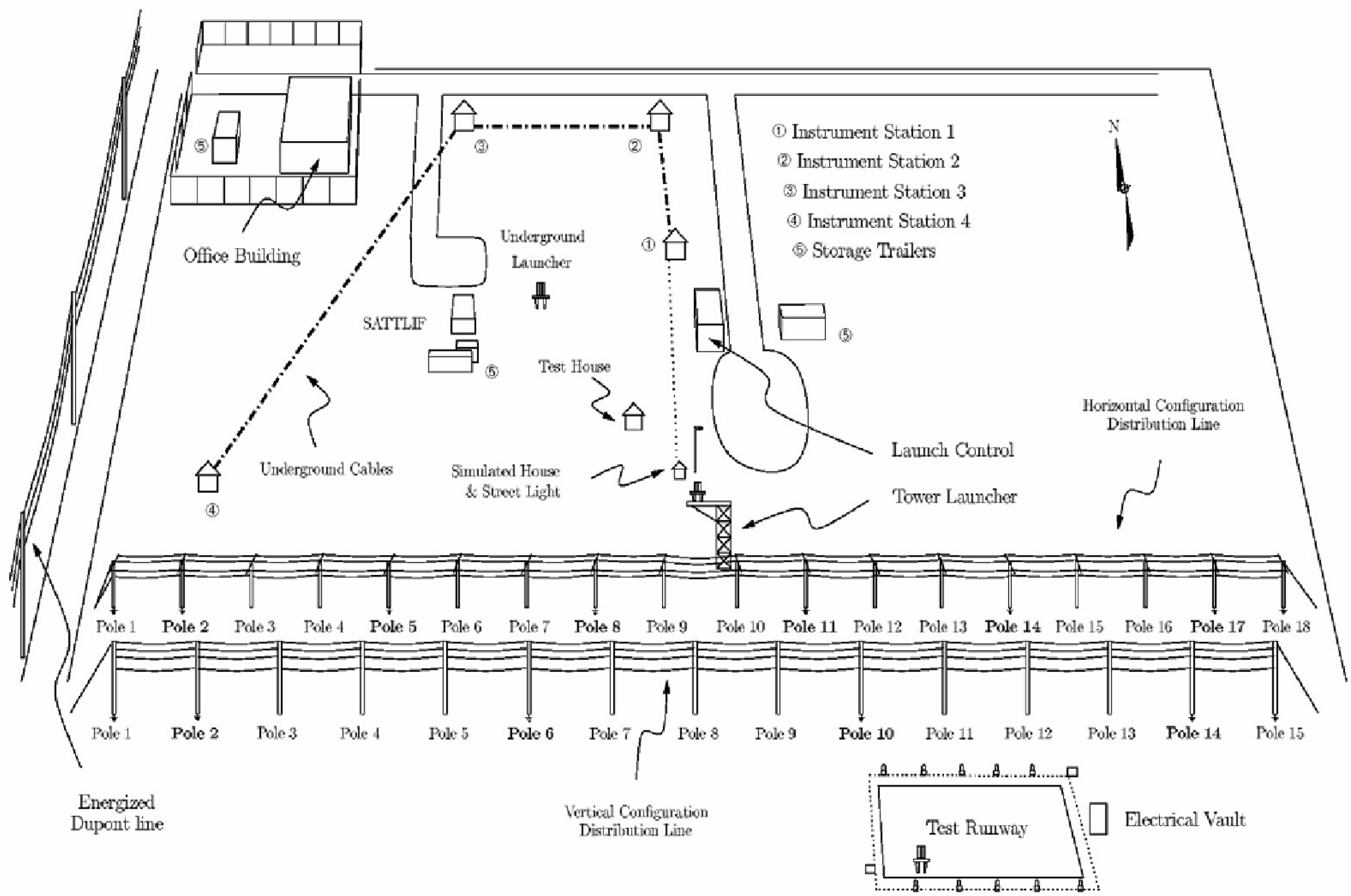

Figure 2-7: International Center for Lightning Research and Testing at Camp Blanding, Florida.

CHAPTER 3
TESTING OF THE PEAK CURRENT SENSOR SYSTEM

We tested the peak current sensor (PCS) system with surge currents generated by a) a Keytek surge current generator and b) a charged capacitor short-circuited through a spark gap, c) rocket triggered lightning, and d) natural lightning. A current measurement system consisting of a traditional current sensor (a current transformer or a non-inductive resistor (shunt)) and a digitizing oscilloscope recorded the test current including peak value. All PCS cards read zero before each experiment.

Types of Test Current Waveforms

The PCS system was tested with surge currents from different sources. Each source created a surge current with a different type of current waveshape. The different current waveshapes can be classified as Type I or Type II waveforms. Type I waveforms are unipolar and Type II waveforms are oscillatory. Type I waveforms are further identified as fast, slow, or very slow according to the current risetime.

Type I Fast Current Waveform

The Type I fast waveform is unipolar, has a risetime between a fraction of a microsecond and a few microseconds and decays to zero within a few 100s of microseconds. Type I fast waveforms are typically measured at the lightning channel base during natural lightning first return strokes (risetimes in the order of a few microseconds) and natural lightning subsequent / rocket triggered lightning return strokes (risetimes in the order of a fraction of a microsecond). An example of a Type I fast current waveshape is shown in Figure 3-1.

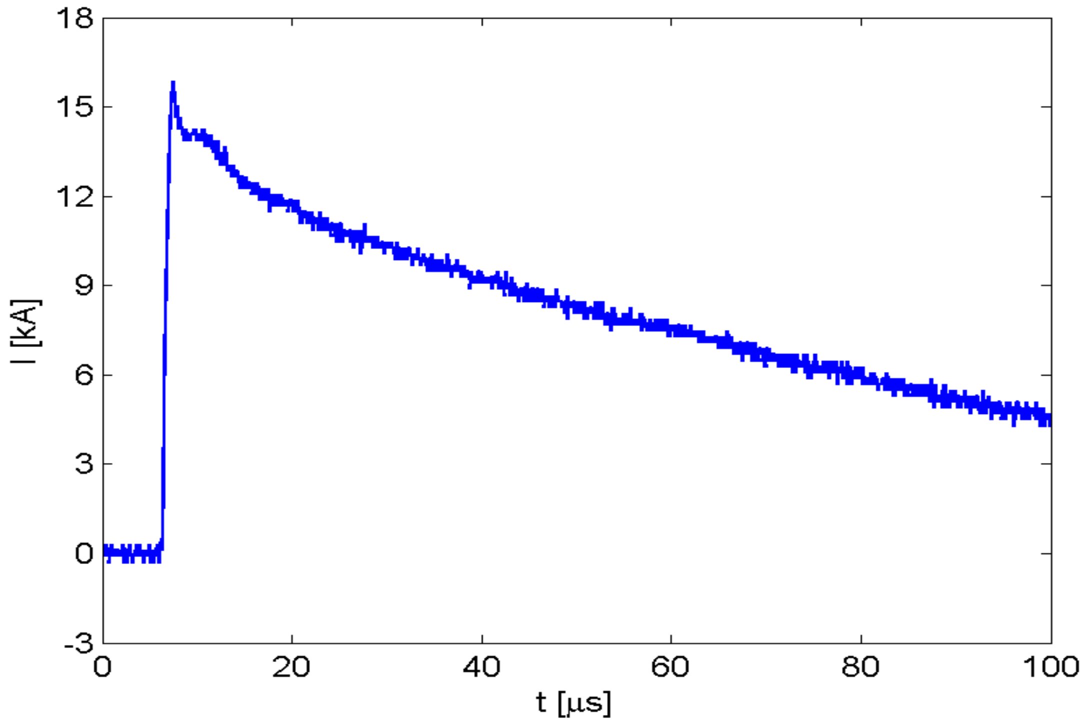

Figure 3-1: Type I fast waveform. Channel base current of flash FPL0403, stroke 1.

Type I Slow Current Waveforms

The Type I slow waveform is unipolar, has a risetime from a few tens to a few hundreds of microseconds and decays to zero within a few 100s of microsecond. Type I slow waveforms are generated by the Keytek generator. Examples of Type I slow waveforms are shown in Figure 3-2 and Figure 3-3.

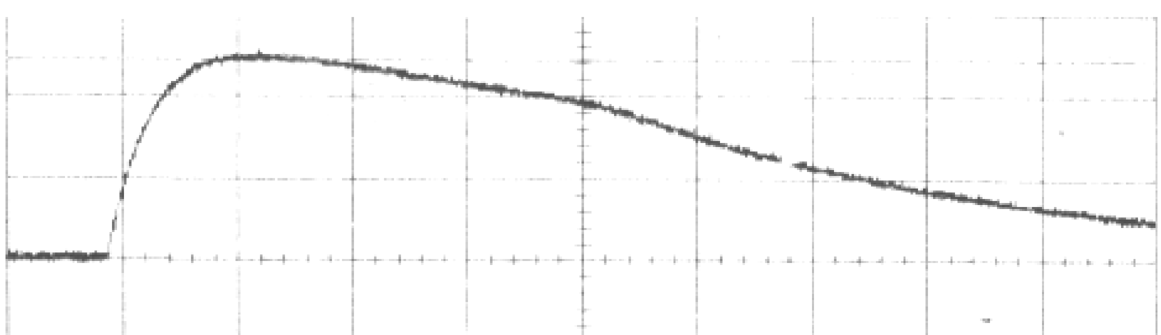

Figure 3-2: Type I slow waveform (vertical axis: 1 kA/division, horizontal axis: 50 μs/ division). Generated by Keytek generator connected to a low impedance load.

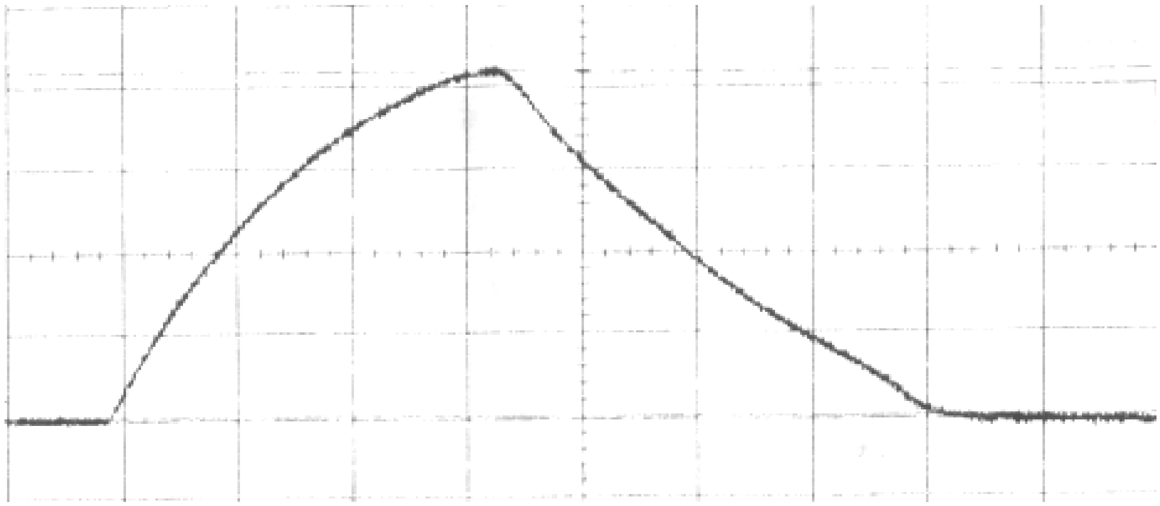

Figure 3-3: Type I very slow waveform (vertical axis: 2 kA/ division, horizontal axis: 50 μs/division). Generated by Keytek generator connected to high impedance.

Type II Current Waveform

Type II waveforms are bipolar and have the shape of a decaying sine wave that oscillates with a period of the order of some 10s of microseconds. Type II waveforms are generated by short circuiting a charged capacitor through a spark gap. An example of a Type II waveform is shown in Figure 3-4.

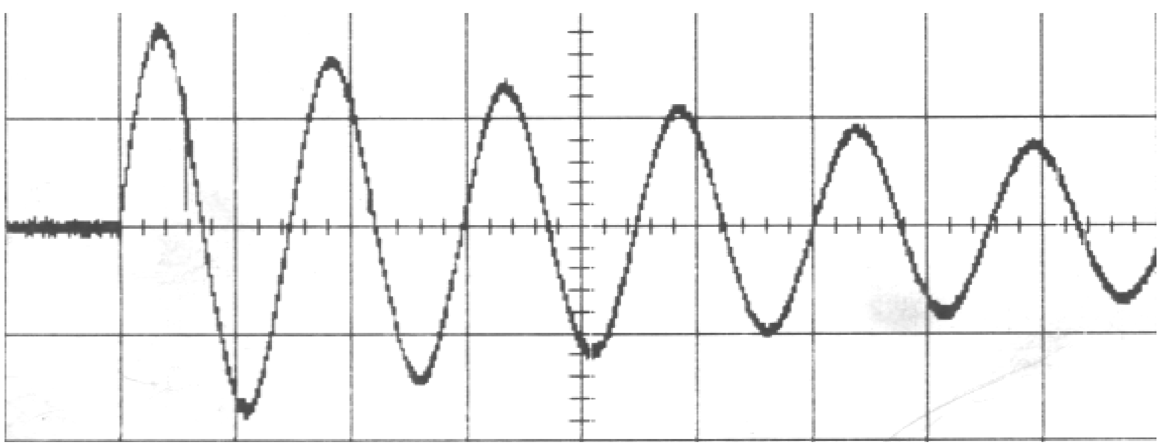

Figure 3-4: Type II waveform (vertical axis: 2 kA/division, horizontal axis 20 μs/division). Generated by a discharging a capacitor.

Keytek Experiment

A Keytek current generator was used to produce a test surge current. The nominal maximum output of the Keytek generator is 500 A, which is below the lower measurement limit of the PCS system. In an attempt to generate currents (magnetic fields) within the measurement limits of the PCS card system, we formed multiple loops of the wire connecting the generator terminals and measured the current through the bundled loop with the result that the measured current should be the sum of the current through each individual turn.

The risetime of the generated current increases with the numbers of turns – e.g., the current waveform shown in Figure 3-2 (risetime approximately 50 μs) was measured through a 20 turn loop, the current waveform shown in Figure 3-3 (risetime approximately 170 μs) was measured through a 62 turn loop. Increasing the number of turns increases the impedance of the load connected to the generator, which causes a reduction of the current through each individual turn. Therefore, increasing the number of turns does not necessarily result in a larger total current through all turns.

For the PCS measurement we read the exposed cards n times with the magnetic card reader. The current through the bundled loop was measured with a Pearson Electronics current transformer (Model 110A) which has a frequency response from 1 Hz to 20 MHz and an 8 bit LeCroy Oscilloscope (Model Waverunner LT344L) set to sample at 20 MHz.

The outcomes of the Keytek experiments are summarized in Table 3-1. The complete data are found in the Appendix. Table 3-1 includes the Experiment ID, the PCS card ID, the number of turns of the bundled loop (Turn #), the rise time of the generated current from zero to peak (RT), the decay time of the generated current from peak to zero (DT), the peak current measured by the current transformer and oscilloscope ($Peak_{Osc}$) , the number of times we read the exposed PCS card (n), and the average value ($Peak_{PCS}$, Average) and standard deviation ($Peak_{PCS}$, Std. Dev.) of the n readings.

We placed the cards with the four possible different orientations into the card holder without detecting a difference in the measured value of zero (see Table 3.1). Apparently the placement of the card does not influence the measurement.

The PCS card/card reader system failed to detect the small (3 kA to 5 kA) unipolar surge currents generated with the Keytek generator. This suggests that the lower measurement limit for the PCS system is above 5 kA and not at 3 kA, as stated by OBO Bettermann. Note that for two events (Experiment 6 and 10) the card reader read 16 kA for both first readings and 0 kA for all other readings. Perhaps the card reader did not know how to interpret a marginal disturbance of the original magnetic field on the stripe.

Table 3-1: Summary of Keytek experiment.

Exp. ID	**Card ID**	**Turn #**	**RT [μs]**	**DT [μs]**	**$Peak_{Osc}$ [kA]**	**n**	**$Peak_{PCS}$ Average [kA]**	**$Peak_{PCS}$ Std. Dev. [kA]**	**Comments**
1	6	20	50	450	2.7	5	3.2	7.2	first reading: 16 kA, all other readings: 0 kA
2	7	42	200	100	4.5	3	0	0	-
3	7	62	200	100	4.7	3	0	0	card orientation: magnetic stripe faces up
4	7	62	200	100	4.8	3	0	0	card orientation: magnetic stripe faces down
5	8	63	200	100	4.2	3	0	0	card orientation: magnetic stripe faces up and opposite of closing latch.
6	9	63	200	100	4.2	3	0	0	card orientation: magnetic stripe faces down and opposite of closing latch.
7	10	85	200	100	4.4	6	2.7	6.5	first reading: 16 kA, all other readings: 0 kA

Capacitor Discharge Experiments

A discharging capacitor was used to generate the test surge current. We charged a capacitor until the voltage across a spark gap exceeded the breakdown voltage of the spark gap. The spark gap triggered and short-circuited the capacitor terminals causing a surge current that rapidly discharged the capacitor. The gap size of the spark gap determines the breakdown voltage which determines the charge on the capacitor and hence the magnitude of the discharge current. We measured the discharge current with a Pearson Electronics current transformer (Model 110A) which has a frequency response from 1 Hz to 20 MHz and an 8 bit LeCroy Oscilloscope (Model Waverunner LT344L) set to sample at 20 MHz. For some experiments we added an inductance in series with the discharge circuit in an attempt to filter out any high frequency spikes in the initial discharge breakdown current. We used two different configurations for the capacitor discharge experiment: (1) A short discharge current path and (2) a long discharge current path.

Capacitor Discharge Experiment with Short Discharge Current Path

The discharge current path in this experiment is approximately one meter long. The capacitor, the spark gap, and the inductance are shown in Figure 3-5 and Figure 3-6. The current transformer is shown in Figure 3-5 and the PCS card and holder are shown in Figure 3-6. The test current waveshapes are of Type II (see Figure 3-4). The capacitor discharge currents had some high frequency noise in the beginning (Figure 3-7). Note that the bandwidth of the current transformer (20 MHz) is possibly not large enough to measure the peak of the noise.

The outcomes of the capacitor discharge experiments are summarized in Table 3-2. The complete data are found in the Appendix. Table 3-2 includes the Experiment ID, the

PCS card ID, the number of turns of added inductance (Turn #), the period of the generated current, the largest current peak measured by the current transformer and oscilloscope ($Peak_{Osc}$) , the number of times we read the exposed PCS card (n), and the average value ($Peak_{PCS}$, Average) and standard deviation ($Peak_{PCS}$, Std. Dev.) of the n readings.

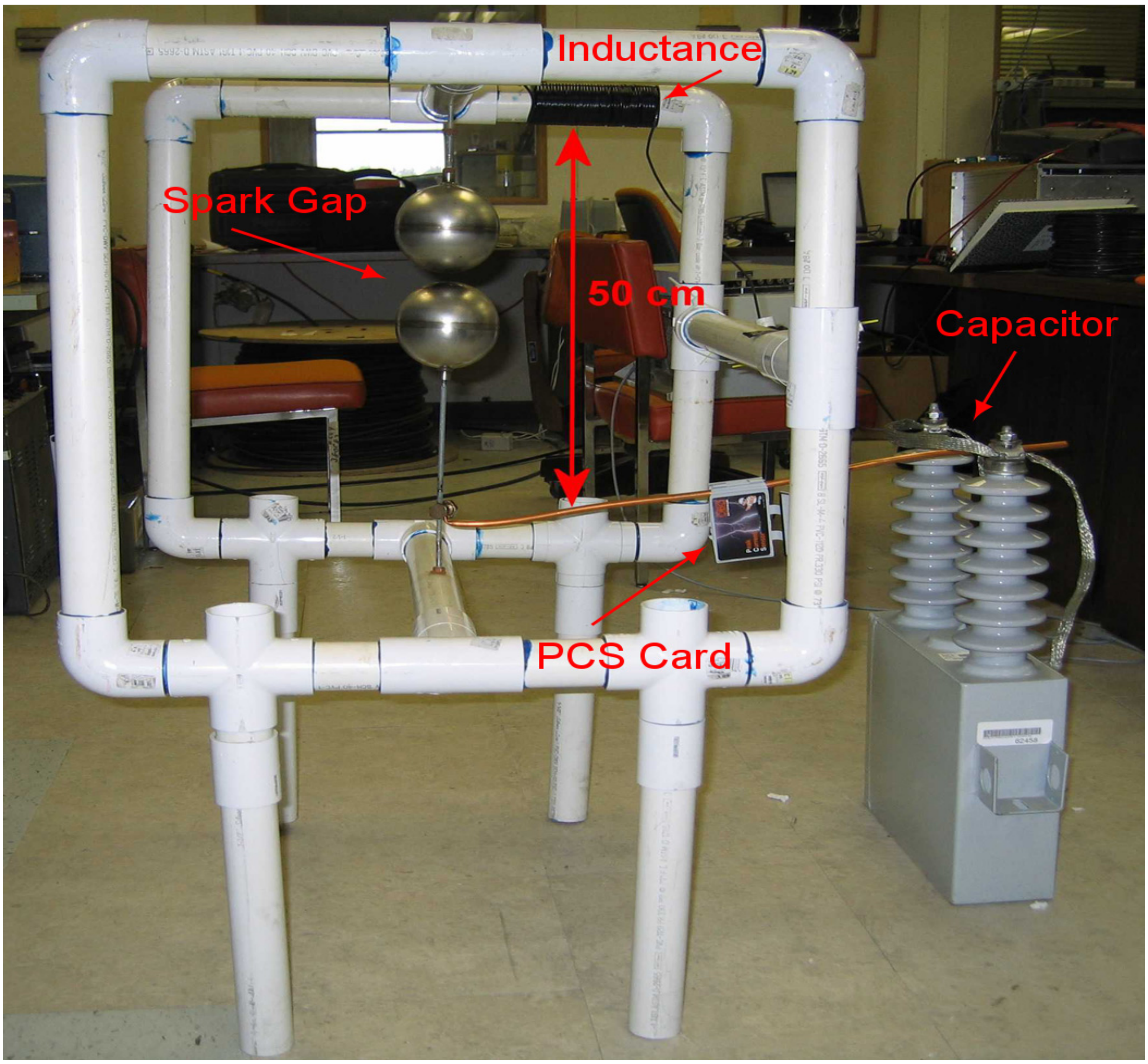

Figure 3-5: Capacitor, spark gap, PCS card and holder, and inductance; side view.

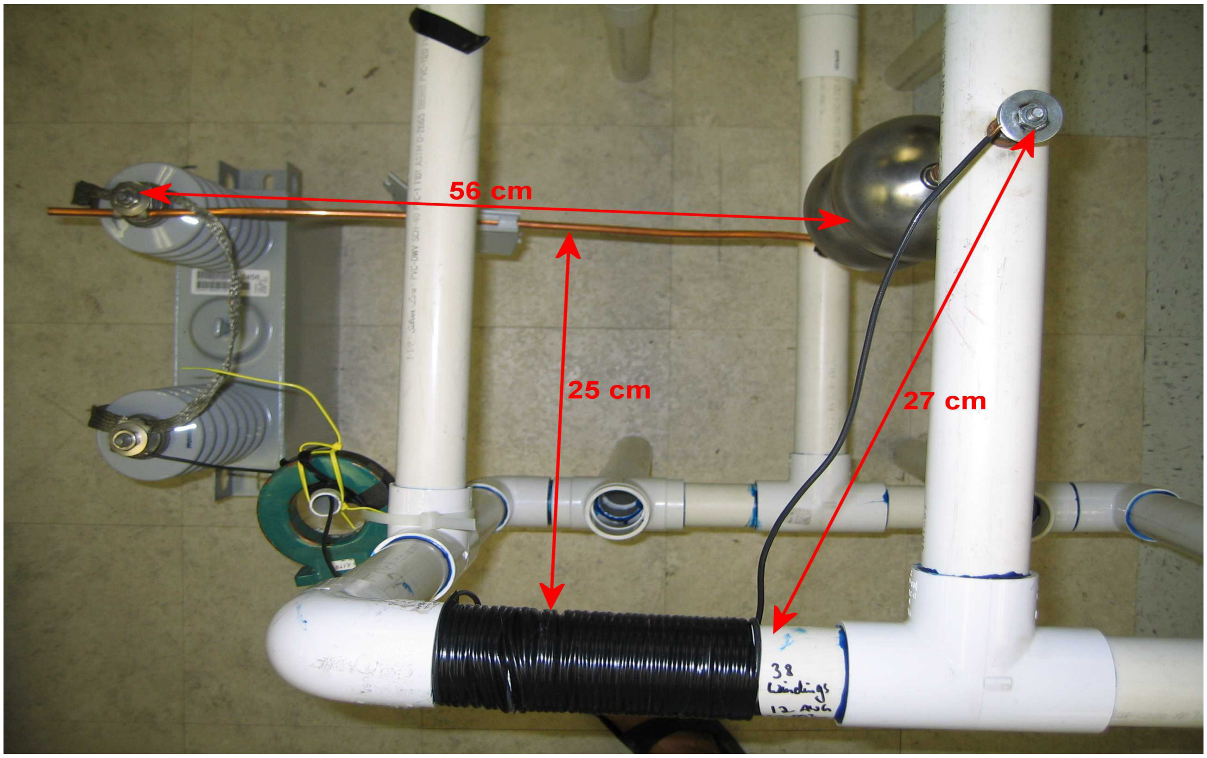

Figure 3-6: Capacitor, spark gap, current transformer, and inductance; bird's eye view.

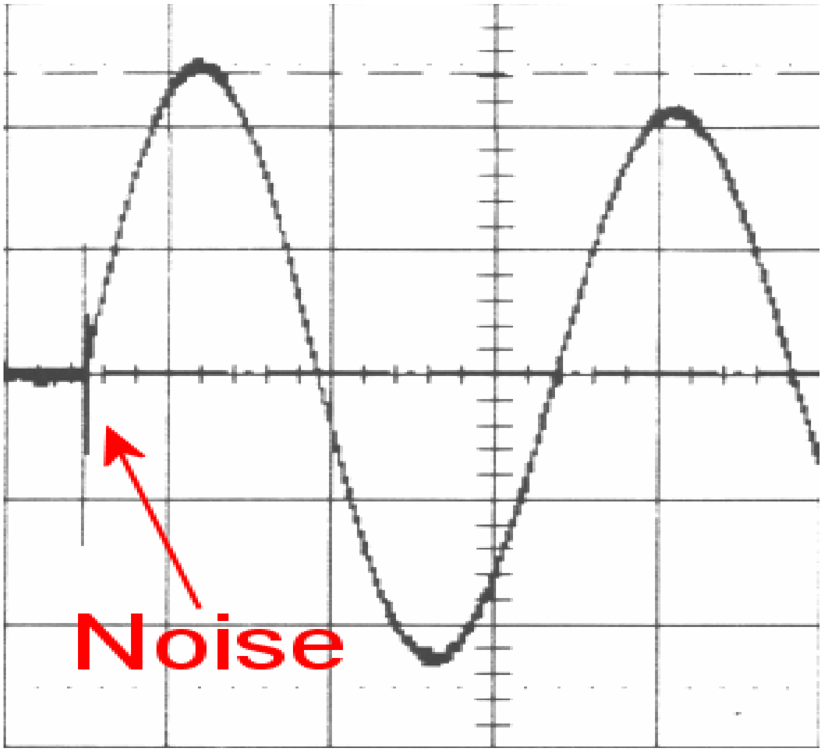

Figure 3-7: Oscillatory capacitor discharge current. Noise is discernable at the beginning of the discharge process.

Table 3-2: Summary of the capacitor discharge experiment.

Exp. ID	Card ID	Turn #	Period [μs]	$Peak_{Osc}$ [kA]	n	$Peak_{PCS}$ Average [kA]	$Peak_{PCS}$ Std. Dev. [kA]	Comments
8	1	0	17	6.8	15	33.5	4.2	7 readings were 31 kA, 3 readings were 41 kA
9	1	0	17	14	4	41	0	-
10	2a	0	17	12	3	41	0	we measured the surge current with 2 cards simulatenously
10	2b	0	17	12	3	41	0	
11	4	0	17	4	9	12.2	2.6	first reading: 19 kA, all other readings: 11 kA or 12 kA
12	11	appr. 10	29	5	10	10.5	1.0	added inductance
13	12	appr. 10	29	7	10	21.8	1.7	added inductance

Capacitor Discharge Experiment with Long Discharge Current Path

We modified the capacitor discharge experiment by creating a longer path for the discharge current in an attempt to create measurement points for the cards that have less exposure to the direct electromagnetic radiation from the discharge circuit. We also added more PCS cards – some of the newly added cards were placed about 10 cm or about 15 cm from the current-carrying wire (not in a card holder) to see if they would detect any electromagnetic interference. We increased the sampling rate of the LeCroy Oscilloscopes from 20 MHz to 250 MHz or 500 MHz.

Figure 3-8 shows the capacitor and spark gap in the foreground and a chair with the current transformer and PCS cards in the background. The wire from the capacitor to the chair is approximately 3 m long. Figure 3-9 shows two PCS cards placed without card holder under the spark gap with the magnetic stripe perpendicular and parallel to the current discharge path and 2 card holders including PCS cards that are attached to the wire. Figure 3-10 shows two PCS cards without card holder placed under the wire with the magnetic stripe perpendicular and parallel to the current discharge path and a card holder containing a PCS card attached to the wire. We did not add any additional inductance to the circuit.

The test current waveshapes are of Type II (shown in Figure 3-4). The outcomes of the modified capacitor discharge experiments are summarized in Table 3-3. The complete data are found in the Appendix. Table 3-3 includes the Experiment ID, the PCS card ID, the period of the generated current, the largest current peak measured by the current transformer and oscilloscope ($Peak_{Osc}$) , the number of times we read the exposed PCS card (n), the average value ($Peak_{PCS}$, Average) and standard deviation ($Peak_{PCS}$, Std. Dev.) of the n readings, and the PCS card location.

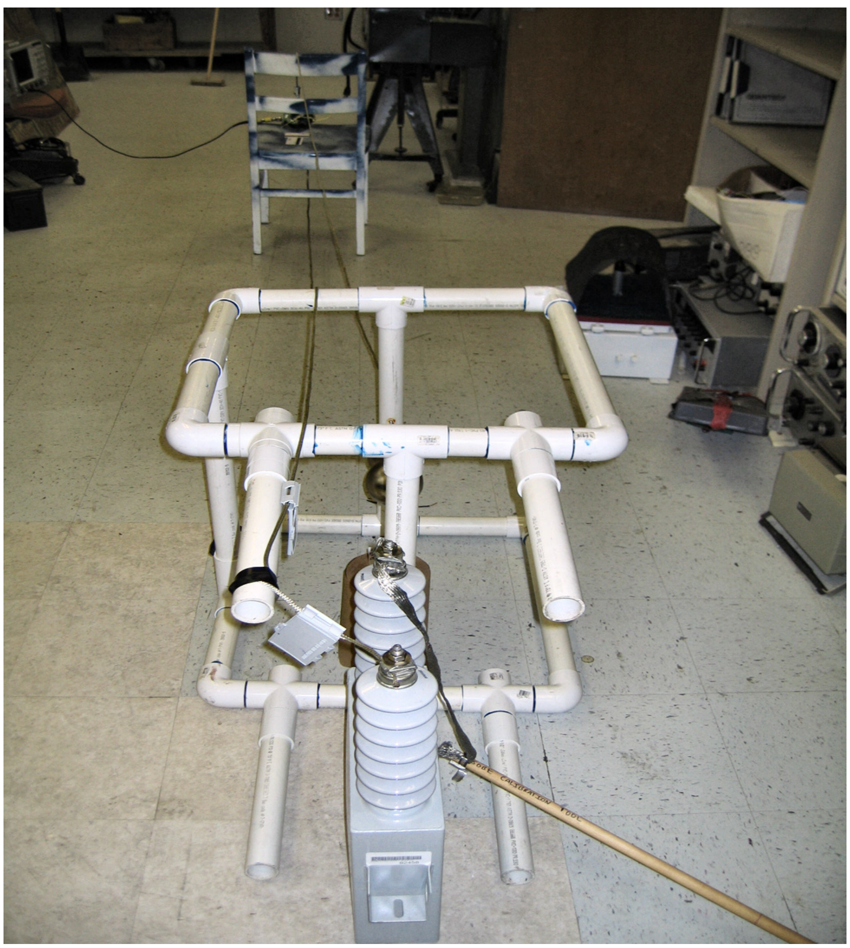

Figure 3-8: Modified capacitor discharge experiment: capacitor and spark gap in the foreground, chair with PCS cards and current transformer in the background.

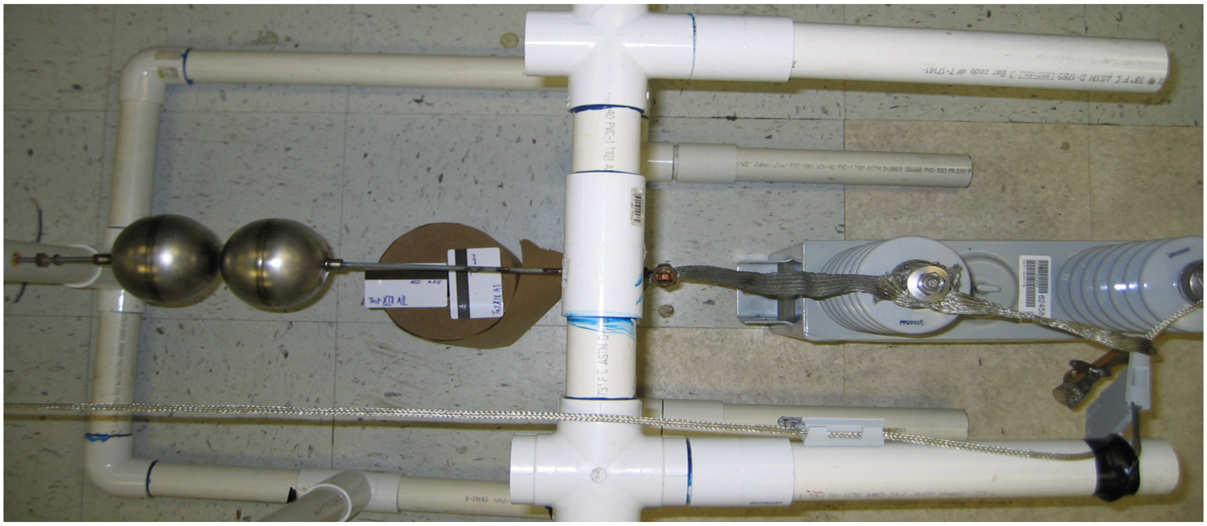

Figure 3-9: Capacitor and spark gap, with two PCS cards placed under the spark gap having the magnetic stripe parallel and perpendicular to the discharge current path and two PCS cards (card 19A1, and 19C) placed inside the card holder attached to the wire.

Figure 3-10: Measurements points at approximately 3 m from the capacitor. Two PCS cards are placed under the wire on a chair with the magnetic stripe parallel and perpendicular to the discharge current path and one PCS cards is placed inside the card holder attached to the wire.

Table 3-3: Summary of the modified capacitor discharge experiment

Exp. ID	Card ID	Period [μs]	$Peak_{Osc}$ [kA]	n	$Peak_{PCS}$ Average [kA]	$Peak_{PCS}$ Std. Dev. [kA]	PCS Card Location	Comments
14	15	29	> 16	10	22.6	2.6	attached to the wire hanging over the chair	Oscilloscope measurement saturated at 16 kA
15	16	29	16.6	10	18	1.9	attached to the wire hanging over the chair	-
16	17	29	15	10	16	0	attached to the wire hanging over the chair	-
16	17A	29	15	2	0	0	on the floor about 30 cm under the spark gap	-
16	17B	29	15	10	47.1	6.5	on the chair about 15 cm from the wire	5 readings read 41 kA
17	18A1	29	12	10	24.5	7.7	attached to the wire close to the capacitor	-
17	18A2	29	12	3	0	0	about 10 cm under the spark gap	-
17	18B1	29	12	10	12.9	1.2	attached to the wire hanging over the chair	-
17	18B2	29	12	11	49.3	19.3	on the chair about 15 cm from the wire	8 readings read 41 kA, 1 reading read 105 kA
18	19A1	29	10	10	15.8	3.4	attached to the wire close to the capacitor	-
18	19A2	29	10	10	0	0	about 10 cm under the spark gap, perpendicular orientation	-
18	19A3	29	10	10	14.4	33.7	about 10 cm under the spark gap, parallel orientation	first reading: 41 kA, 4th reading 103 kA, all other readings: 0 kA
18	19B1	29	10	10	8.2	1.0	attached to the wire hanging over the chair	-
18	19B2	29	10	10	42.4	4.4	on the chair about 15 cm from the wire, perpendicular orientation	9 readings read 41 kA
18	19B3	29	10	10	41	0	on the chair about 15 cm from the wire, parallel orientation	-
18	19C	29	10	10	24.5	14.1	attached to the wire close to the capacitor	-

Summary of the Capacitor Discharge Experiments

Generally, the current peaks from the PCS cards installed on the current carrying wire and close to the spark gap were much larger than the currents observed by the current transformer and oscilloscope while the current peaks of the cards installed on the current carrying wire with the spark gap a few meters away from the card gave proper results. Some of the PCS cards placed about 10 cm or about 15 cm away from the current carrying wire showed non-zero values (one reading of a card placed 15 cm from the current carrying-carrying wire was 105 kA) while other cards showed zero values. The cause of the apparently erroneously high current readings on the cards used in the capacitor discharge experiments is not understood, but the high values may well be related to (1) the direct electromagnetic radiation from the spark gap or from other parts of the current-carrying wire effecting the card's magnetic stripe in an unexpected way, and/or (2) the magnetic field from a potential short duration (nanosecond scale) breakdown current (not observable with our present instrumentation if indeed it does exists) in the current-carrying wire rather than from the oscillatory capacitor discharge current observed on the digitizing oscilloscope.

Lightning Experiments

During the 2004 lightning campaign we measured the channel base current of rocket triggered lightning with the PCS cards. Also, we placed cards on the counterpoise of the ICLRT test runway and on the counterpoise of an igloo located at the nearby Camp Blanding military base.

Rocket Triggered Lightning Experiment

Return stroke currents from rocket-triggered-lightning were injected into the overhead ground wire of a power distribution line.

The initial continuous current (ICC) preceding the return strokes in triggered lightning was conducted to ground through a grounded fuse wire that was attached to the tower launcher. The return strokes attached to the horizontally oriented "U" shape structure (interceptor) above the launch tower that was connected to the overhead ground wire of the power distribution line.

The return stroke current was measured with a T&M Research Products, Inc. current shunt (model R-5600-8) having a frequency response from 0-12 MHz and sampled with an 8 bit LeCroy Waverunner LT344L oscilloscope at 20 MHz (5 ms segments, bandwidth limit: 5 MHz) and a 12 bit Yokogawa DL716 oscilloscope at 2 MHz (2 s long continuous record, bandwidth limit: 500 kHz). Three PCS cards attached to the wire connecting the interceptor structure and the overhead ground wire measured the channel base current peak. The three PCS card holders with cards, the current shunt, the interceptor structure, and the rocket launcher are shown in Figure 3-11.

It was not possible to change the PCS cards between strokes of a multi-stroke flash and was usually not safe to change the cards between flashes occurring at the same day. Therefore, one set of cards was typically exposed to multiple currents.

During the 2004 experiment we obtained one set of PCS cards (cards 1A, 2A, and 3A) that were installed on the wire connecting the interceptor structure with the test distribution line. This set was exposed to the following currents:

- The ICC of event FPL0402: This event did not contain any return strokes, but an unusual large 9 kA ICC.
- The first stroke of the two stroke flash FPL0403 (Figure 3-12): The channel base current of this stroke peaked at 16 kA. The channel base current is shown in Figure 3-13 on two time scale. The 2 ms window at the top was recorded with the Yokogawa Oscilloscope. The 100 µs window at the bottom was recorded with the LeCroy Oscilloscope.
- The second stroke of the two stroke flash FPL0403: The channel base current of this stroke peaked at 6 kA.

The arithmetic means of 10 readings of the exposed PCS cards 1A and 3A were 15.8 kA (Standard Deviation: 0.8 kA) and 15.3 (Standard Deviation: 1.3), respectively. The arithmetic mean of 9 readings of the exposed PCS card 2A was 17.7 (Standard Deviation: 0.5). Note that the first reading of PCS card 2A (28 kA) was omitted, since the individual who read the card possibly read it incorrectly. The complete data are found in the Appendix.

The reading results of all three cards were very similar to the largest lightning current to which the cards were exposed to (the 16 kA channel base current of stroke 1 in flash FPL0403). According to the manufacturer, the card is designed to maintain a record of only the largest current (magnetic field) to which it is exposed. The PCS cards measured the lightning current peak to within 10% of the measurement by the research equipment.

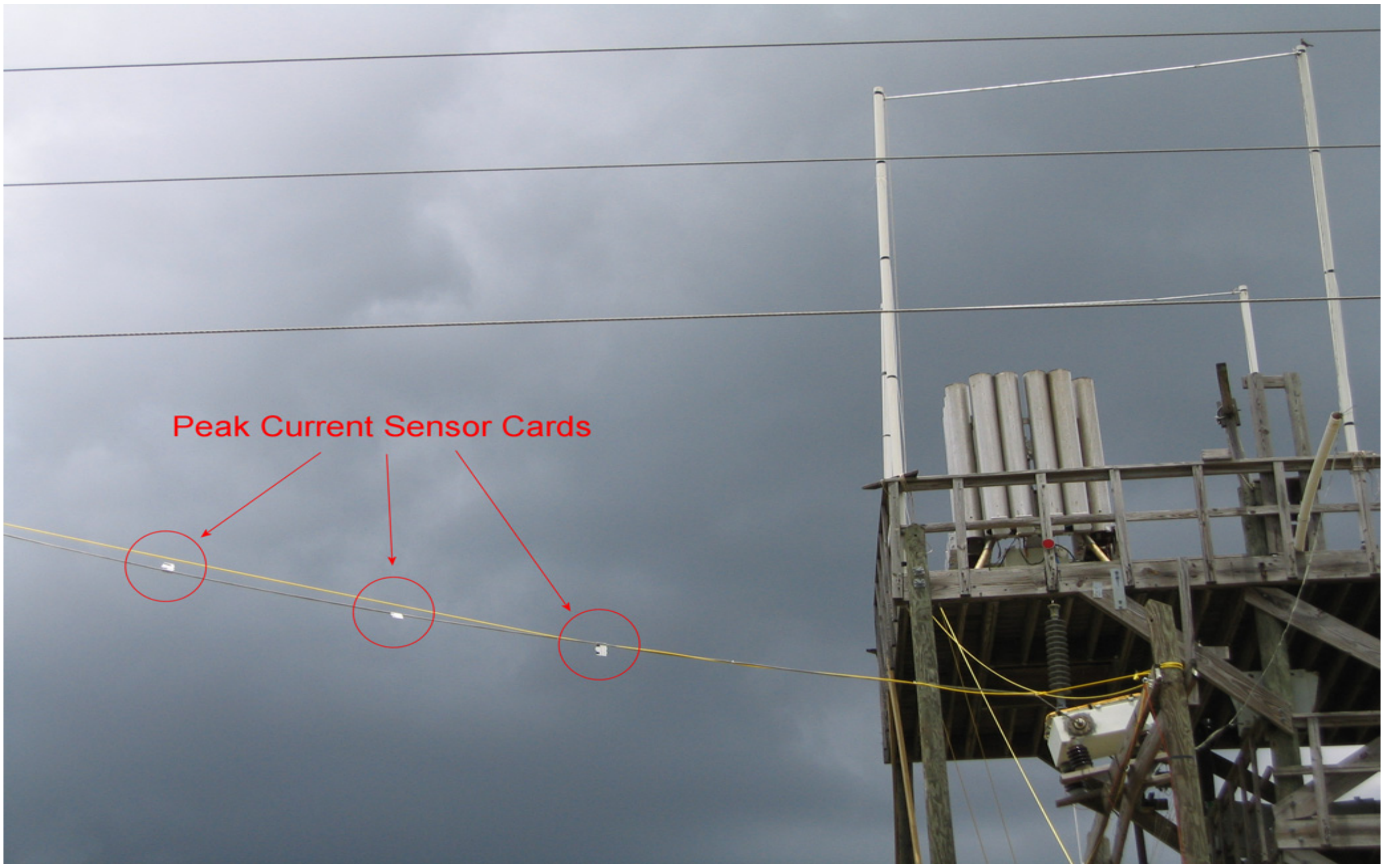

Figure 3-11: Peak current sensor cards 1A, 2A, and 3A (from right to left) to measure the lightning channel base current are placed on the wire connecting the interceptor structure and the power line overhead ground wire. The rocket launcher and the interceptor structure are shown to the right. The current shunt is inside the metal box shown at the bottom right.

Figure 3-12: Two stroke flash FPL0403.

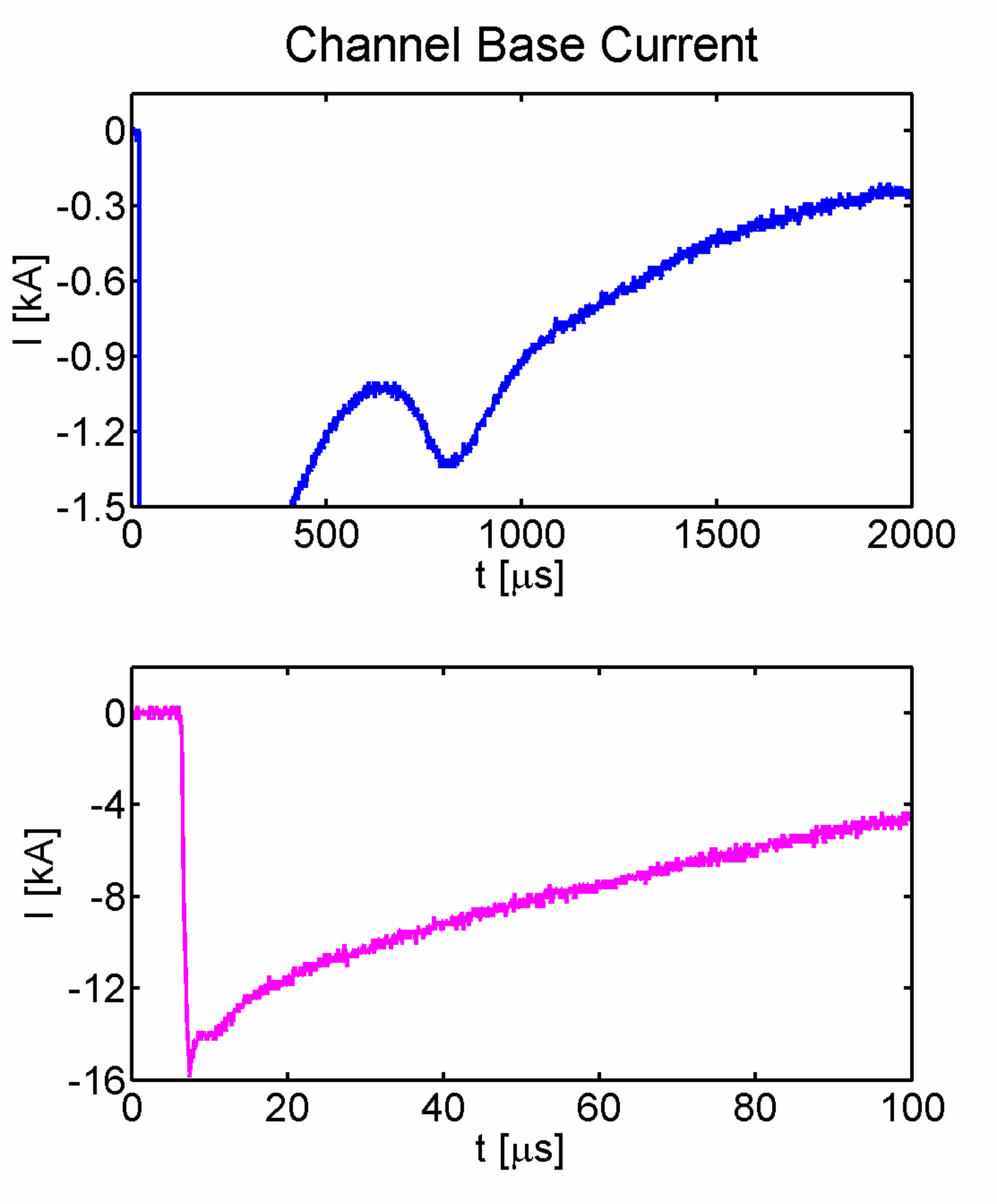

Figure 3-13: Channel base current of stroke 1 in flash FPL0403 displayed on a 2 ms and a 100 μs time scale.

Counterpoise Experiments

We placed 12 PCS cards on the counterpoise of the ICLRT test runway (see Figure 2-7). We had several nearby natural and rocket triggered lightning events during the 2004 lightning season. At the end of the lightning season we read each of the 12 cards at least 10 times and all reading results showed 0 kA, with the exception of the reading of the card labeled C1D (located at the North-West corner of the runway counterpoise), the card labeled C6B (located at the South-East corner of the runway counterpoise), and of the card labeled C9X (located at the South-West corner of the runway counterpoise). Three of the 13 readings for card C1D showed non-zero values. The first, tenth, and eleventh reading showed 5 kA, 7 kA, and 7 kA, respectively. Ten of the 24 readings for card C6B showed non-zero values. The first 6 readings showed 6 kA, 5 kA, 8 kA, 41 kA, 5 kA, and 5 kA. The sixteenth reading showed 15 kA and the twentieth through twenty-second readings showed 7 kA, 5 kA, and 7 kA.

One of the 10 reading results for card C9X showed a non-zero value. The second reading showed 29 kA.

We placed 5 PCS cards on the counterpoise of an explosive storage igloo located on the nearby Camp Blanding military camp. At the end of the lightning season we read each card at least 10 times. All cards read 0 kA, with the exception of the reading of the card labeled Igloo2. Two of the 16 reading results showed non-zero values. The fifth reading of this card showed 6 kA and the seventh reading showed 12 kA.

Other Experiments

We placed cards on the ground leads of 3 test power distribution line poles that were close to the injection point of the rocket-triggered lightning current (i.e., midspan between poles 7 and 8). We placed 3 cards on the ground lead at pole 8 and 1 card each on the ground leads at poles 7 and 9. We installed the cards after the first and only day when we injected rocket-triggered lightning currents into the line. At the end of the season we read the cards 10 times. All cards read 0 kA, as expected.

We installed one card on a ground lead of a light pole that was located on the Camp Blanding army base close to one of the igloos. At the end of the season we read the card 10 times. All readings showed 0 kA.

CHAPTER 4
CONCLUSION AND RECOMMENDATIONS

The OBO Betterman PCS card/card reader system worked properly for measuring the channel base current peak of the largest current in one triggered lightning event (all lightning channel base currents are unipolar). The cards were exposed to one large ICC and two return strokes and registered the peak of the largest current (i.e., the 16 kA return stroke). We recommend more such measurements on triggered lightning currents.

The PCS card/card reader system failed to detect the small (3 kA to 5 kA) unipolar surge currents generated with the Keytek generator. This suggests that the lower measurement limit for the PCS system is above 5 kA and not at 3 kA, as stated by OBO Bettermann. However, two of the seven cards showed non-zero values on their first readings. Both values were 16 kA, which were much larger values than the peaks measured by the current transformer and oscilloscope.

The card/card reader system usually did not work properly when exposed to oscillatory currents from a capacitor discharge ranging from 4 kA to 17 kA. The current peaks from the PCS cards installed on the current carrying wire and close to the spark gap were much larger than the currents observed by the current transformer and oscilloscope while the current peaks of the cards installed on the current carrying wire with the spark gap a few meters away from the card gave proper results. Some of the PCS cards placed about 10 cm or about 15 cm away from the current carrying wire showed non-zero values (one reading of a card placed 15 cm from the current carrying-carrying wire was 105 kA) while other cards showed zero values. This gives some indication that the apparently erroneously high results of the cards installed on the current-carrying wire were caused by direct radiation from the spark gap or from other parts of the current-carrying wire. Alternatively, it could be that the cards measure the peak of the high-frequency noise discernable at the beginning of the discharge current and that the 20 MHz bandwidth of the current transformer is not high enough to measure the peak. We need to determine under which circumstances the cards give proper results and under which circumstances the results are erroneous. We recommend additional experiments with cards placed at regular intervals on and near the current-carrying wire to find out at which locations the cards give proper results and to determine if direct radiation causes the erroneous readings on the cards. In addition to the above, we recommend that PCS cards be placed at the ICLRT magnetic field measurement stations to correlate the measured magnetic fields with potentially erroneous card readings.

The cards on the two counterpoises exposed to nearby triggered and natural lightning generally measured zero current with some exceptions where in a sequence of measurements on a single card there were mainly zero and a few non-zero measurements.

We very strongly recommend examining the magnetic structure on the stripes of all the cards exposed in 2004 to try to resolve the various ambiguities discussed in this report concerning erroneous and anomously high card readings.

APPENDIX
PCS CARD READINGS

The following tables contain all readings obtained from the PCS system for the Keytek experiment, the capacitor discharge experiment, the modified capacitor discharge experiment, and the rocket-triggered lightning experiment. The tables also include arithmetic means and standard deviations of the PCS system measurements, and the largest current peak measured with a conventional current sensor and digital oscilloscope.

Table A1: Keytek experiment PCS card readings.

KEYTEK EXPERIMENT

Experiment ID: 1
Card ID: 6
Oscilloscope: 2.7 kA

PCS System	
Reading	**Value [kA]**
1	16
2	0
3	0
4	0
5	0
Average	***3.2***
Std. Dev.	***7.2***

Experiment ID: 2
Card ID: 7
Oscilloscope: 4.5 kA

PCS System	
Reading	**Value**
1	0
2	0
3	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 3
Card ID: 7
Oscilloscope: 4.7 kA

PCS System	
Reading	**Value**
1	0
2	0
3	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 4
Card ID: 7
Oscilloscope: 4.8 kA

PCS System	
Reading	**Value**
1	0
2	0
3	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 5
Card ID: 8
Oscilloscope: 4.2 kA

PCS System	
Reading	**Value**
1	0
2	0
3	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 6
Card ID: 9
Oscilloscope: 4.2 kA

PCS System	
Reading	**Value**
1	0
2	0
3	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 7
Card ID: 10
Oscilloscope: 4.4 kA

PCS System	
Reading	**Value**
1	16
2	0
3	0
4	0
5	0
6	0
Average	***2.7***
Std. Dev.	***6.5***

Table A2: Capacitor discharge experiment PCS card readings..

CAPACITOR DISCHARGE EXPERIMENT

Experiment ID: 8
Card ID: 1
Oscilloscope: 6.8 kA

PCS System	
Reading	**Value [kA]**
1	41
2	41
3	32
4	41
5	37
6	31
7	30
8	31
9	31
10	31
11	31
12	31
13	34
14	30
15	31
Average	***33.5***
Std. Dev.	***4.2***

Experiment ID: 9
Card ID: 1
Oscilloscope: 14 kA

PCS System	
Reading	**Value**
1	41
2	41
3	41
4	41
Average	***41.0***
Std. Dev.	***0.0***

Experiment ID: 10
Card ID: 2a
Oscilloscope: 12 kA

PCS System	
Reading	**Value**
1	41
2	41
3	41
Average	***41.0***
Std. Dev.	***0.0***

Experiment ID: 10
Card ID: 2b
Oscilloscope: 12 kA

PCS System	
Reading	**Value**
1	41
2	41
3	41
Average	***41.0***
Std. Dev.	***0.0***

Experiment ID: 11
Card ID: 4
Oscilloscope: 4 kA

PCS System	
Reading	**Value [kA]**
1	19
2	12
3	12
4	11
5	11
6	11
7	12
8	11
9	11
Average	***12.2***
Std. Dev.	***2.6***

Experiment ID: 12
Card ID: 11
Oscilloscope: 5 kA

PCS System	
Reading	**Value**
1	13
2	11
3	10
4	10
5	11
6	10
7	10
8	10
9	10
10	10
Average	***10.5***
Std. Dev.	***1.0***

Experiment ID: 13
Card ID: 12
Oscilloscope: 7 kA

PCS System	
Reading	**Value**
1	23
2	24
3	22
4	20
5	20
6	24
7	20
8	23
9	22
10	20
Average	***21.8***
Std. Dev.	***1.7***

Table A3: Modified capacitor discharge experiment PCS card readings., 1/2.

MODIFIED CAPACITOR DISCHARGE EXPERIMENT 1/2

Experiment ID: 14
Card ID: 15
Oscilloscope: >16 kA

PCS System	
Reading	Value [kA]
1	29
2	22
3	22
4	25
5	21
6	21
7	22
8	22
9	22
10	20
Average	***22.6***
Std. Dev.	***2.6***

Experiment ID: 15
Card ID: 16
Oscilloscope: 16.6 kA

PCS System	
Reading	Value [kA]
1	21
2	18
3	22
4	17
5	18
6	17
7	17
8	17
9	16
10	17
Average	***18.0***
Std. Dev.	***1.9***

Experiment ID: 16
Card ID: 17
Oscilloscope: 15 kA

PCS System	
Reading	Value [kA]
1	16
2	16
3	16
4	16
5	16
6	16
7	16
8	16
9	16
10	16
Average	***16.0***
Std. Dev.	***0.0***

Experiment ID: 16
Card ID: 17A
Oscilloscope: 15 kA

PCS System	
Reading	Value
1	0
2	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 16
Card ID: 17B
Oscilloscope: 15 kA

PCS System	
Reading	Value [kA]
1	52
2	53
3	41
4	41
5	41
6	54
7	53
8	41
9	54
10	41
Average	***47.1***
Std. Dev.	***6.5***

Experiment ID: 17
Card ID: 18A1
Oscilloscope: 12 kA

PCS System	
Reading	Value [kA]
1	23
2	36
3	41
4	20
5	23
6	19
7	19
8	19
9	25
10	20
Average	***24.5***
Std. Dev.	***7.7***

Experiment ID: 17
Card ID: 18A2
Oscilloscope: 12 kA

PCS System	
Reading	Value [kA]
1	0
2	0
3	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 17
Card ID: 18B1
Oscilloscope: 12 kA

PCS System	
Reading	Value [kA]
1	13
2	13
3	13
4	15
5	12
6	12
7	12
8	12
9	12
10	15
Average	***12.9***
Std. Dev.	***1.2***

Table A4: Modified capacitor discharge experiment PCS card readings., 2/2

MODIFIED CAPACITOR DISCHARGE EXPERIMENT 2/2

Experiment ID: 17
Card ID: 18B2
Oscilloscope: 15 kA

PCS System	
Reading	**Value [kA]**
1	41
2	55
3	41
4	41
5	41
6	54
7	41
8	41
9	41
10	105
11	41
Average	***49.3***
Std. Dev.	***19.3***

Experiment ID: 18
Card ID: 19A1
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	7
2	18
3	19
4	17
5	18
6	17
7	16
8	15
9	15
10	16
Average	***15.8***
Std. Dev.	***3.4***

Experiment ID: 18
Card ID: 19A2
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
Average	***0.0***
Std. Dev.	***0.0***

Experiment ID: 18
Card ID: 19A3
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	41
2	0
3	0
4	103
5	0
6	0
7	0
8	0
9	0
10	0
Average	***14.4***
Std. Dev.	***33.7***

Experiment ID: 18
Card ID: 19B1
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	9
2	10
3	7
4	8
5	7
6	8
7	8
8	9
9	9
10	7
Average	***8.2***
Std. Dev.	***1.0***

Experiment ID: 18
Card ID: 19B2
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	41
2	41
3	41
4	55
5	41
6	41
7	41
8	41
9	41
10	41
Average	***42.4***
Std. Dev.	***4.4***

Experiment ID: 18
Card ID: 19B3
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	41
2	41
3	41
4	41
5	41
6	41
7	41
8	41
9	41
10	41
Average	***41.0***
Std. Dev.	***0.0***

Experiment ID: 18
Card ID: 19C
Oscilloscope: 29 kA

PCS System	
Reading	**Value [kA]**
1	35
2	41
3	54
4	16
5	23
6	19
7	15
8	15
9	13
10	14
Average	***24.5***
Std. Dev.	***14.1***

Table A5: Rocket-triggered lightning experiment PCS card readings.

ROCKET-TRIGGERED LIGHTNING EXPERIMENT

Card ID: 1A
Oscilloscope: 16 kA

PCS System	
Reading	**Value [kA]**
1	17
2	16
3	16
4	16
5	15
6	15
7	15
8	17
9	16
10	15
Average	***15.8***
Std. Dev.	***0.8***

Card ID: 2A
Oscilloscope: 16 kA

PCS System	
Reading	**Value [kA]**
1	18
2	18
3	17
4	18
5	18
6	18
7	17
8	17
9	18
Average	***17.7***
Std. Dev.	***0.5***

Card ID: 3A
Oscilloscope: 16 kA

PCS System	
Reading	**Value [kA]**
1	18
2	16
3	15
4	16
5	15
6	14
7	16
8	15
9	14
10	14
Average	***15.3***
Std. Dev.	***1.3***

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